Photon counting detectors for the 1.0 - 2.0 μm wavelength range

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Overview

Purpose:

Improve 1.0 - 2.0 μm wavelength laser instrument system margins by improving the detector sensitivity.

Advantages of receiver improvements:

- Equivalent to laser power/energy improvements for most LIDAR applications.
- Typically have low negative system impacts (e.g. little increase in thermal load, weight, power).
- Apply to a wide range of laser technologies
- Allows operation beyond the retinal thermal damage wavelengths (>1.4 micron) (i.e. truly "eye-safe")

Approach

Design and manufacture large area (> 200 μm diameter) InGaAs APDs with materials (InGaAs-Si, InGaAs-InAlAs) and device structures to enhance photon counting.

Goals

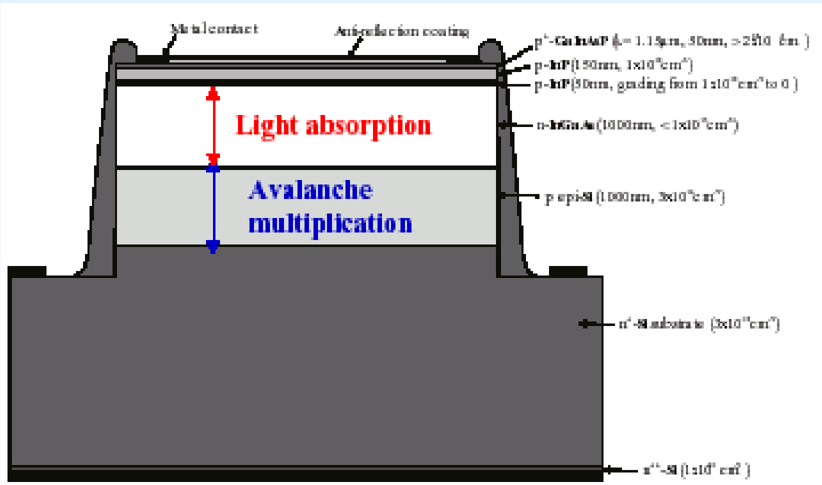
- Photon counting sensitivity over the 1.0 - 2.0 μm wavelength range
- Detection efficiency: 1 - 20%
- Detector size: >200 μm diameter
- Dark counts: < 100 kcps
- Maximum Count Rate: > 10 Mcps
- Solid State APD: InGaAs photocathode, silicon or InAlAs avalanche region. Additional Candidate: Hybrid Photomultiplier

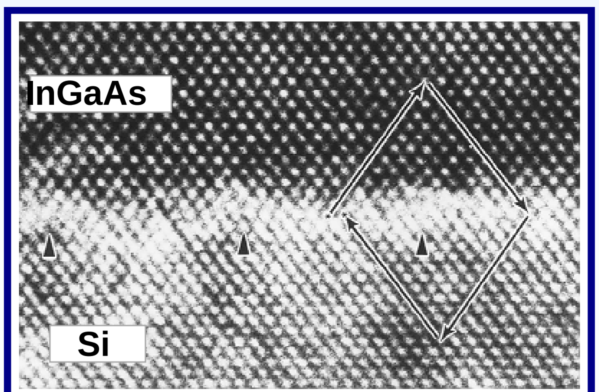
Photon Counting State-of-the-art

	1064 nm Perkin Elmer SPCM	1064 nm Intevac Hybrid PMT	1064 nm InGaAs Array MIT-LL	1550 nm Hamamatsu PMT
Detection Efficiency	2 %	11 %	33%@ 290K	1.5%
Maximum Count Rate	17 Mcps	500 Mcps (device lifetime limited)	1 Mcps @ 210 K (limited by afterpulsing)	Device lifetime limited (10 Mcps)
Dark Counts	200 cps	700 kcps	1.7 Mcps @ 290K 20 kcps @ 210 K	200 kcps
Operating temperature	270 K	290 K	210 K	220 K
Detector size	0.15 mm	1 mm	1.6 mm x 1.6 mm (16 x 16 array microlens)	3 mm x 8 mm

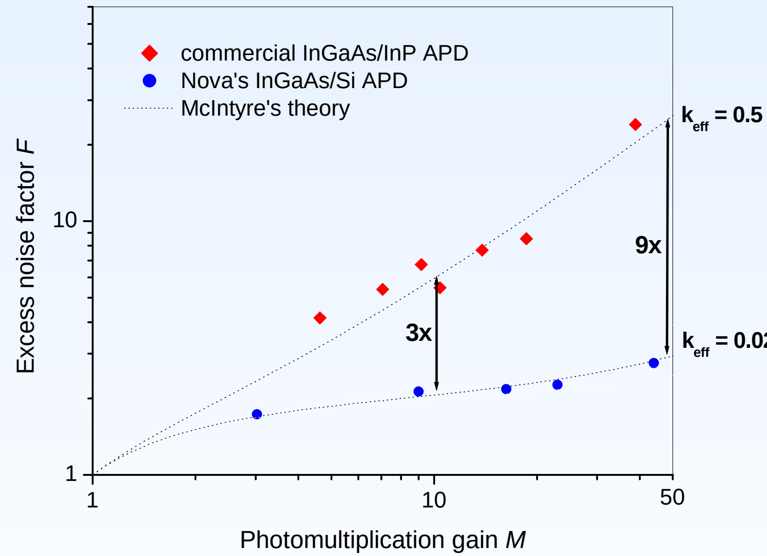
InGaAs-Si APDs - Technical Overview

(made by Nova Crystals Inc. - recently acquired by Gemfire Inc.)





Detector excess noise factor – measured vs. theory



Measured and calculated excess noise for commercial InGaAs/InP APDs and InGaAs/Si APDs. InGaAs/Si s APDs show substantially lower excess noise than the commercial devices. The different curves with effective k-factors were calculated using McIntyre’s theory.

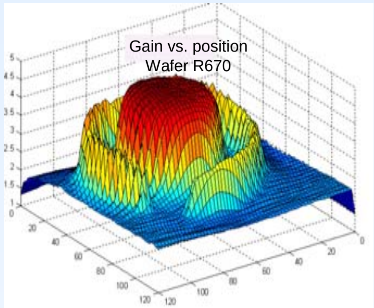
<u>Reference:</u>

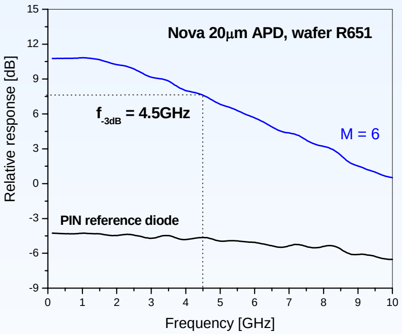
"Fused InGaAs-Si avalanche photodiodes with low-noise performances", Kang Y, Mages P, Clawson AR, Yu PKL, Bitter M, Pan Z, Pauchard A, Hummel S, Lo YH, IEEE PHOTONICS TECHNOLOGY LETTERS 14 (11): 1593-1595 NOV 2002

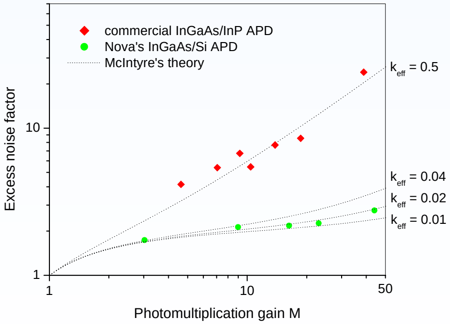
Nova Crystals InGaAs-Si APDs

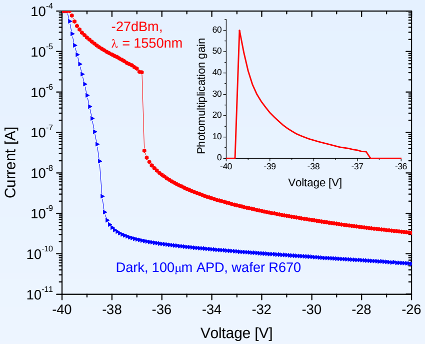
Device results: (at gain of 10)

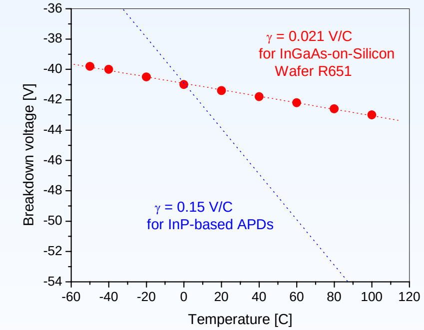
1. Low dark current (< 10nA)
2. High avalanche gain (> 30)
3. High responsivity (> 0.7A/W)
4. Uniform avalanche gain
5. High bandwidth (> 4GHz)
6. Low excess noise factor (< 2.3)
7. Good temperature performance
8. Good reliability (2400hrs at 175°C)

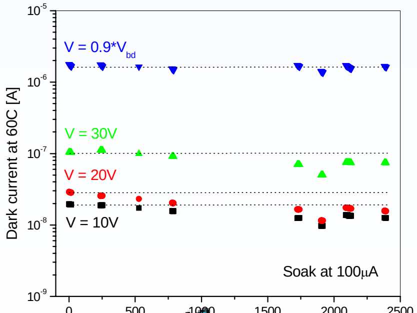




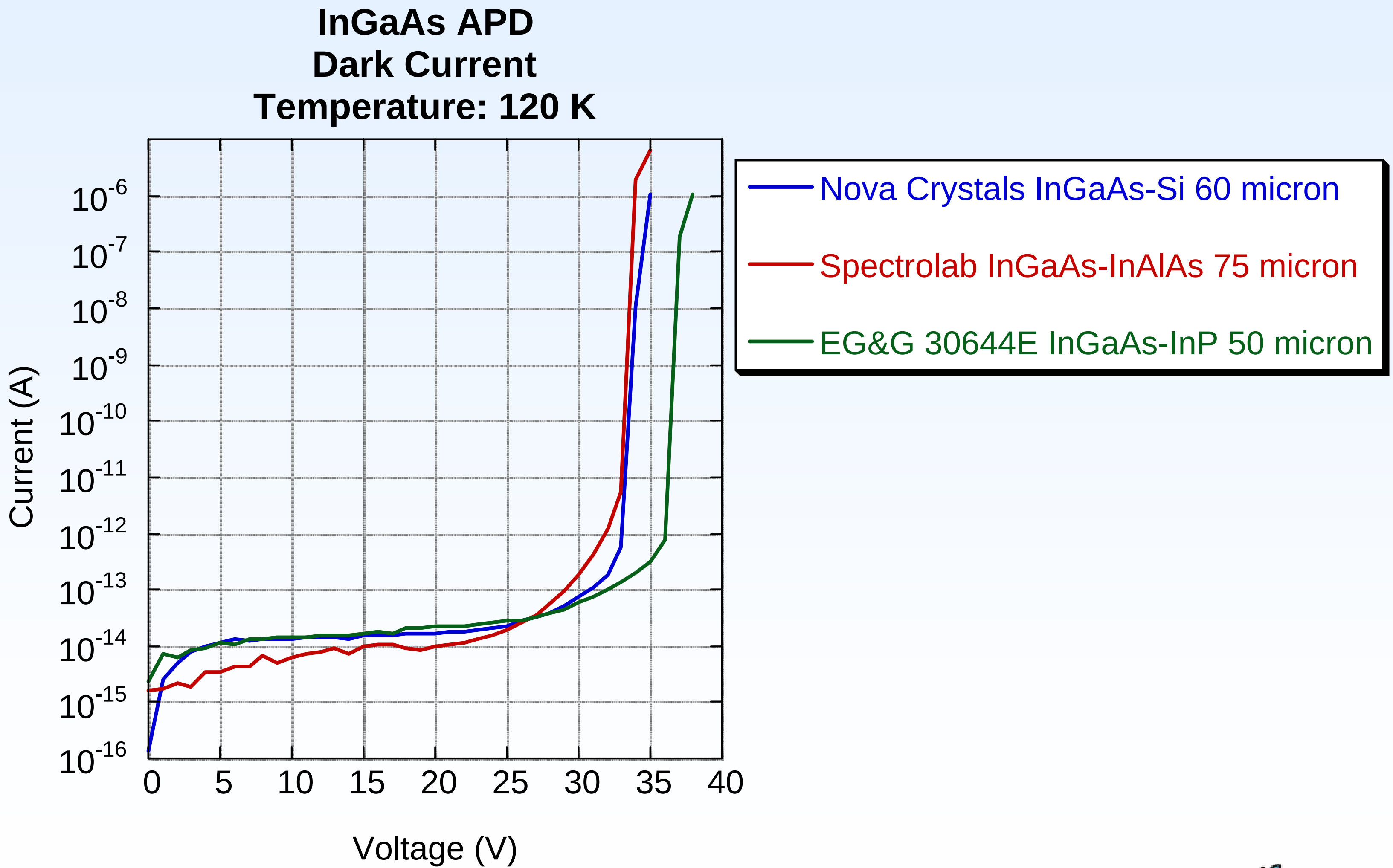




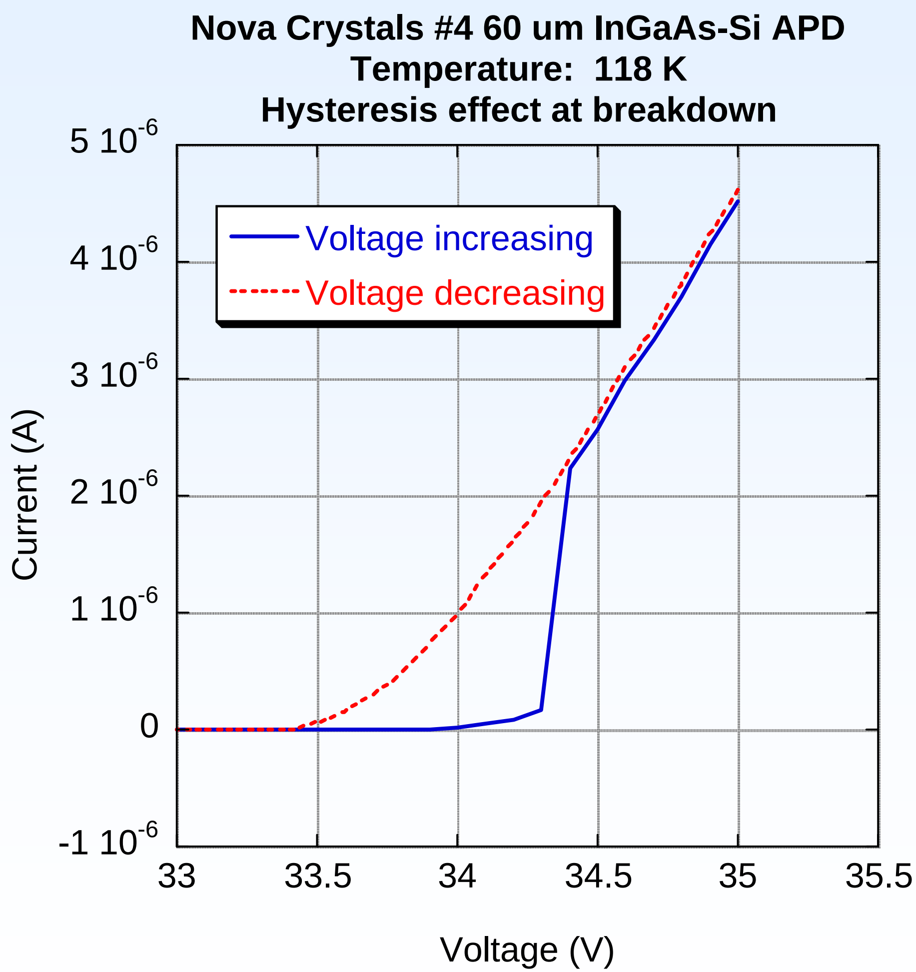




InGaAs APD
Dark Current Comparison



InGaAs-Si APD
Issue: Hysteresis



ELSEVIER

Nuclear Physics B (Proc. Suppl.) 44 (1995) 397–401

NUCLEAR PHYSICS B
PROCEEDINGS
SUPPLEMENTS

Electrical characteristics of Metal-Resistive layer-Silicon (MRS) avalanche detectors

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[b]INFN, Sezione di Padova, via Marzolo 8, 35131 Padova, Italy
[c]Istituto di Elettrotecnica, Università di Cagliari, Piazza d'Armi, 09123 Cagliari, Italy
[d]Laboratory of High Energy, Joint Institute for Nuclear Research, Dubna, Moscow region, 141980, Russia
[e]Institute of Physics, Azerbaijan Academy of Science, Baku, Azerbaijan

The main electrical characteristics at room temperature of Metal-Resistive layer-Silicon avalanche detectors are presented for devices with a Ti/SiC/p-Si structure. Hysteresis of the I-V characteristics and transients taking place during tests at fixed bias have been experimentally studied, in correlation also with the effect of ionizing radiation. The device time response has been tested by using a Sr^{90} source.

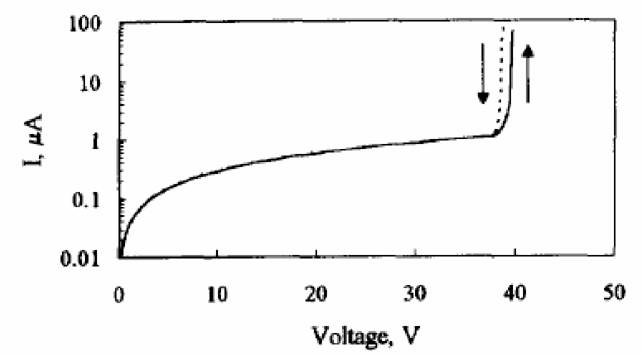
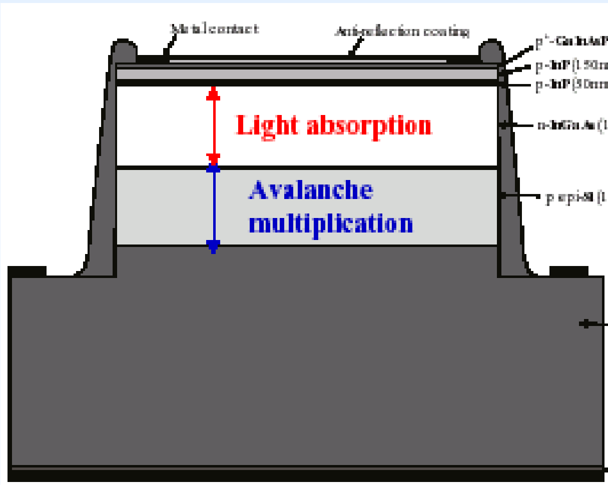
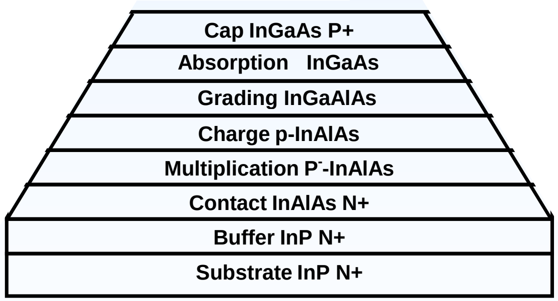


Figure 1. Current-voltage characteristics of a MRS device. Arrows indicate the direction of the voltage sweep.

InGaAs-InAlAs APDs
Overview





Detector excess noise factor

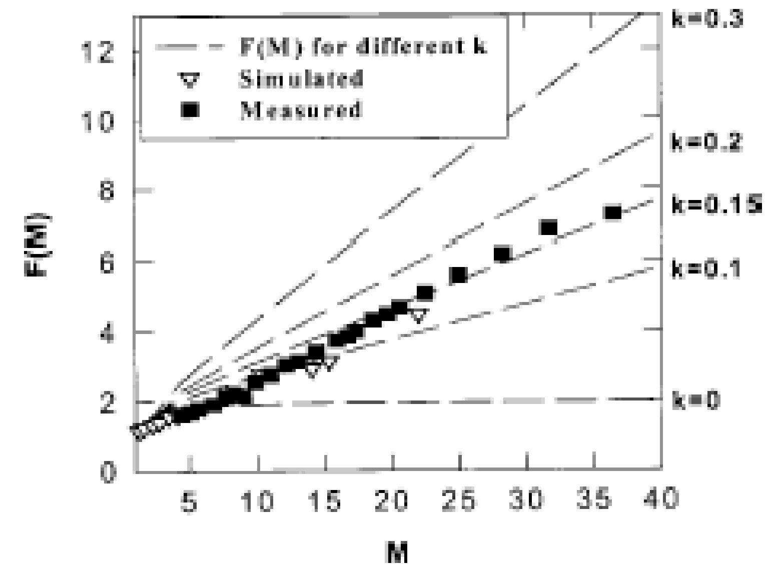


FIG. 3. Simulated and experimental excess noise factor as a function of gain.

Measured and calculated excess noise for InGaAs/InAlAs APDs. InAlAs APDs show substantially lower excess noise (0.15) than the commercial InP devices (0.5).

Reference:

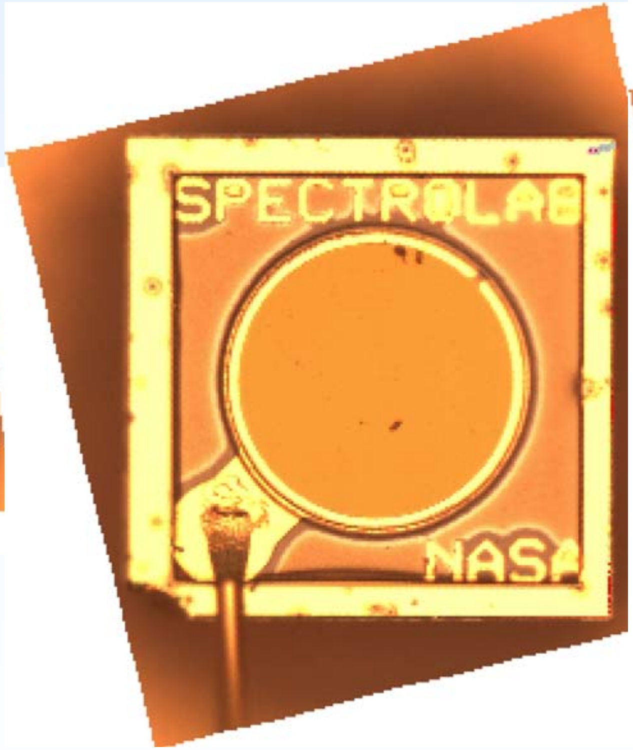
"InGaAs/ InAlAs avalanche **photodiode with undepleted absorber"** Li N, Sidhu R, Li XW, Ma F, Zheng XG, Wang SL, Karve G, Demiguel S, Holmes AL, Campbell JC **APPLIED PHYSICS LETTERS** 82 (13): 2175-2177 MAR 31 200

Abstract: We report an **avalanche** photodiode with an undepleted p-type InGaAs absorption region and a thin **InAlAs** multiplication layer. The motivation for utilizing an undepleted absorption layer, which is similar to that in the unitraveling carrier photodiode, is to reduce the dark current. A dark current below 1 nA at a gain of 10 and a gain-bandwidth product of 160 GHz are demonstrated.

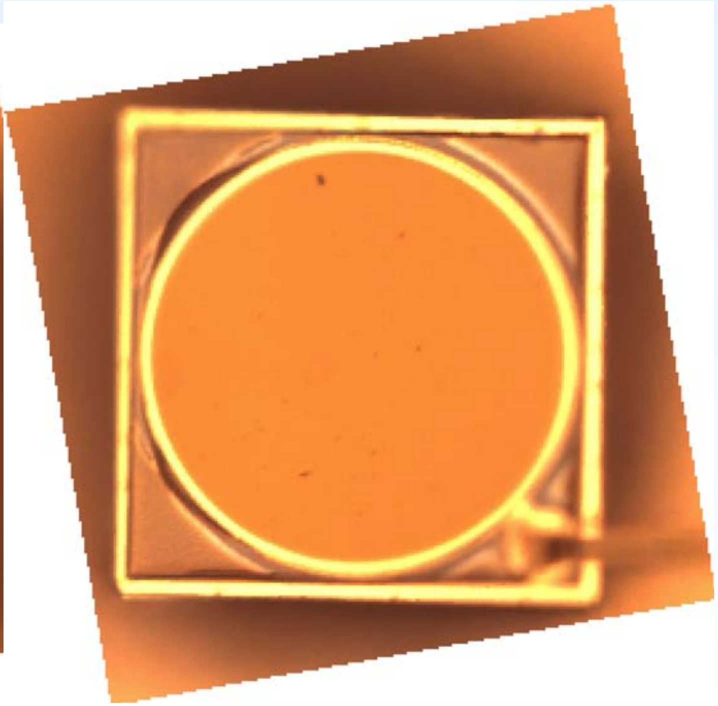
Spectrolab Inc. Custom InGaAs/InAlAs Low-Noise Avalanche Photodiodes (APDs)

Detector Diameter as noted

75 μm

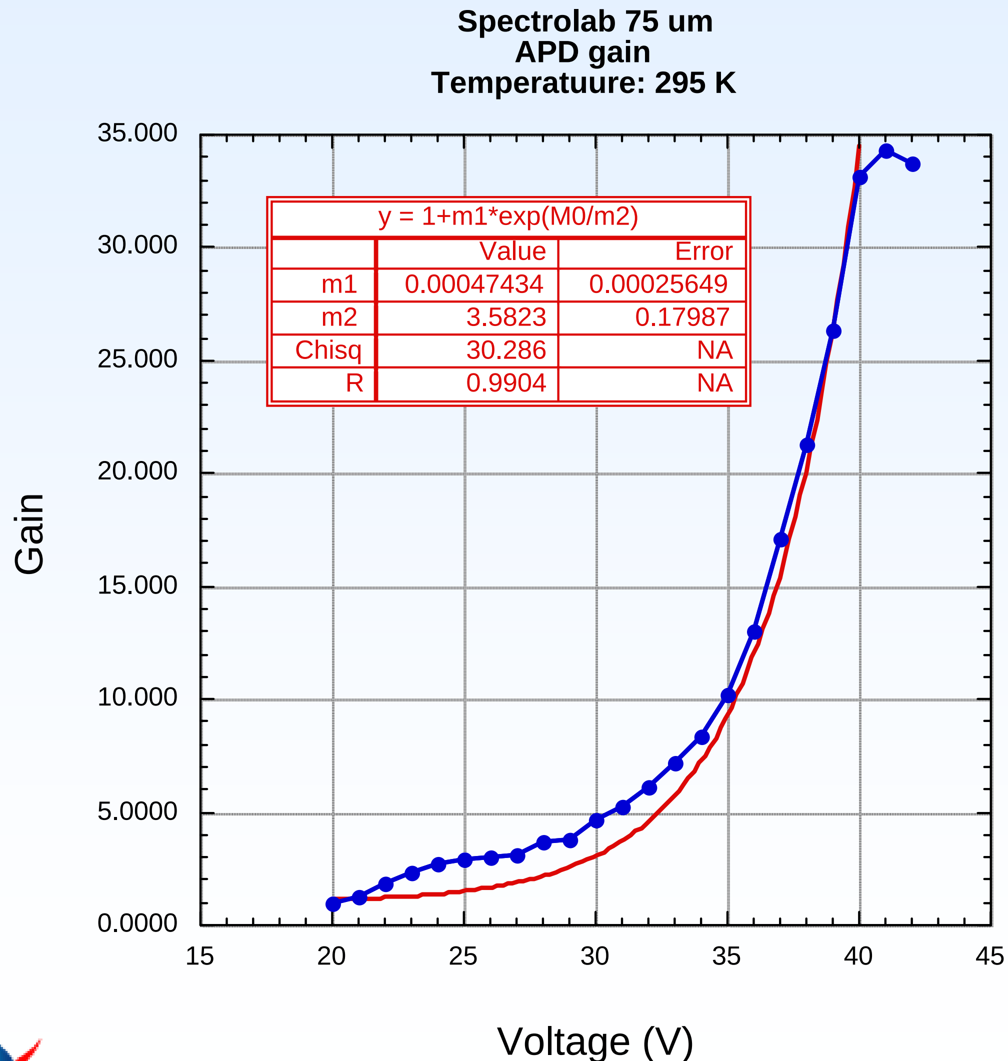


200 μm



300 μm

Spectrolab InGaAs-InAlAs APD Gain at Room Temperature

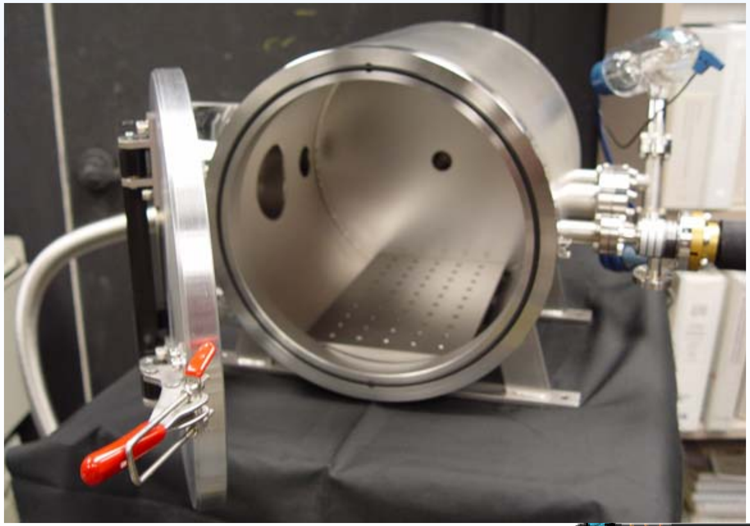


This type of APD has a turn on threshold (punch -through) (in this case ~ 20 V)

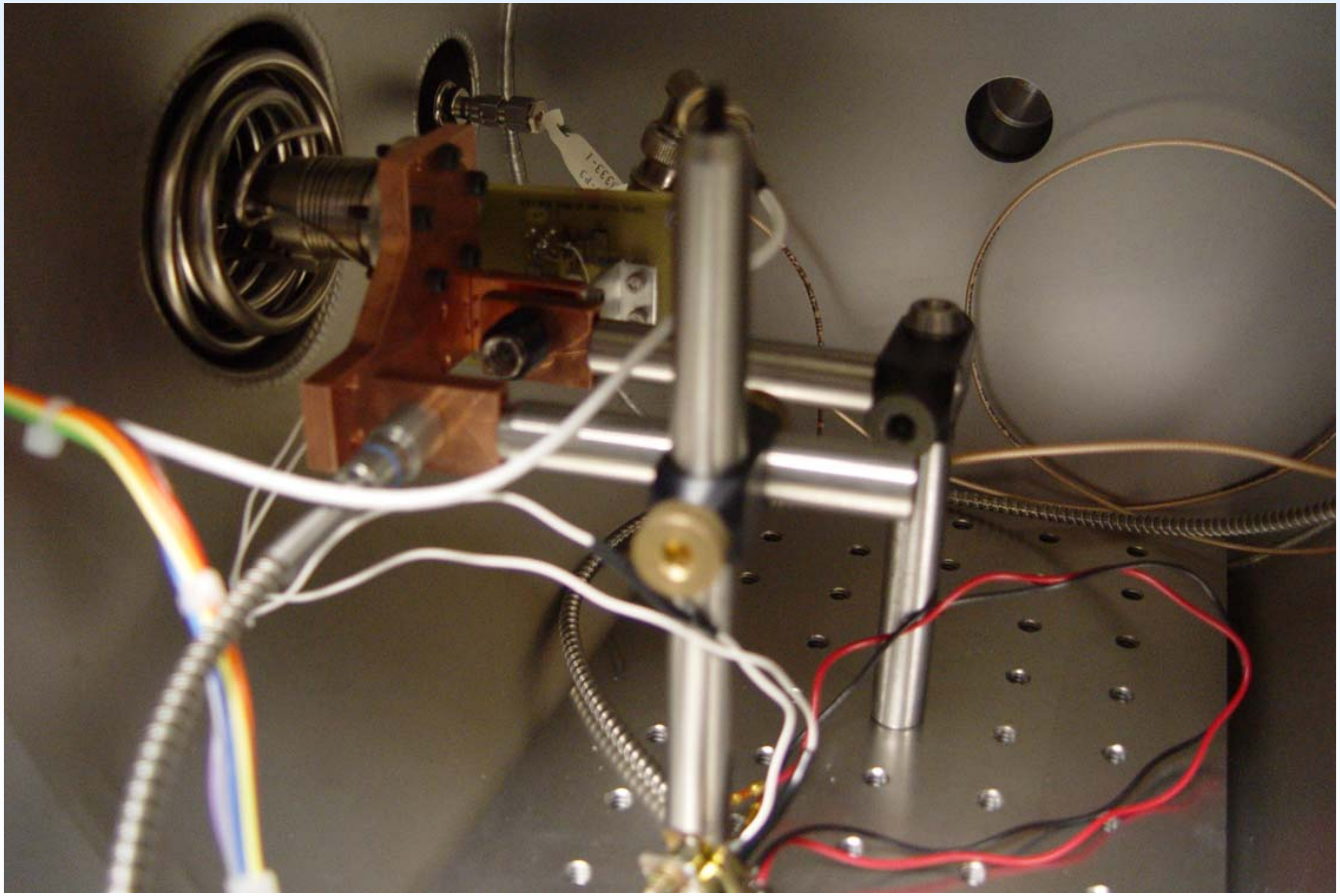
Custom vacuum chamber for cryogenic testing/operation of photon counting detectors (without liquid N2)

Joule-Thompson refrigerator (Cryotiger) for cooled (70K) APD photon counting testing

Cold Finger

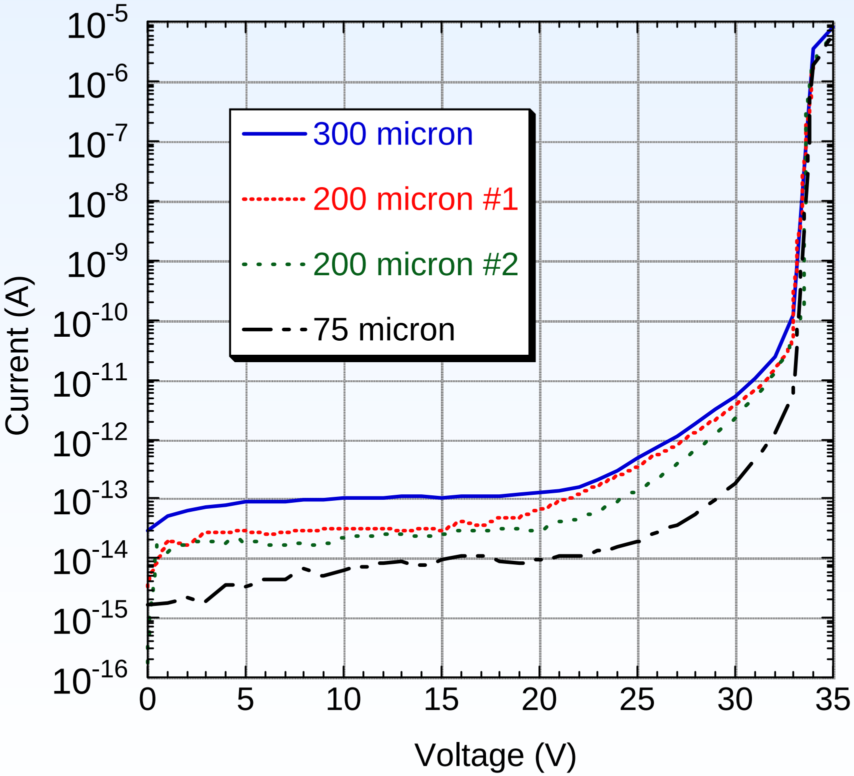


Optical and electrical circuit for cryogenic testing/operation of photon counting detectors

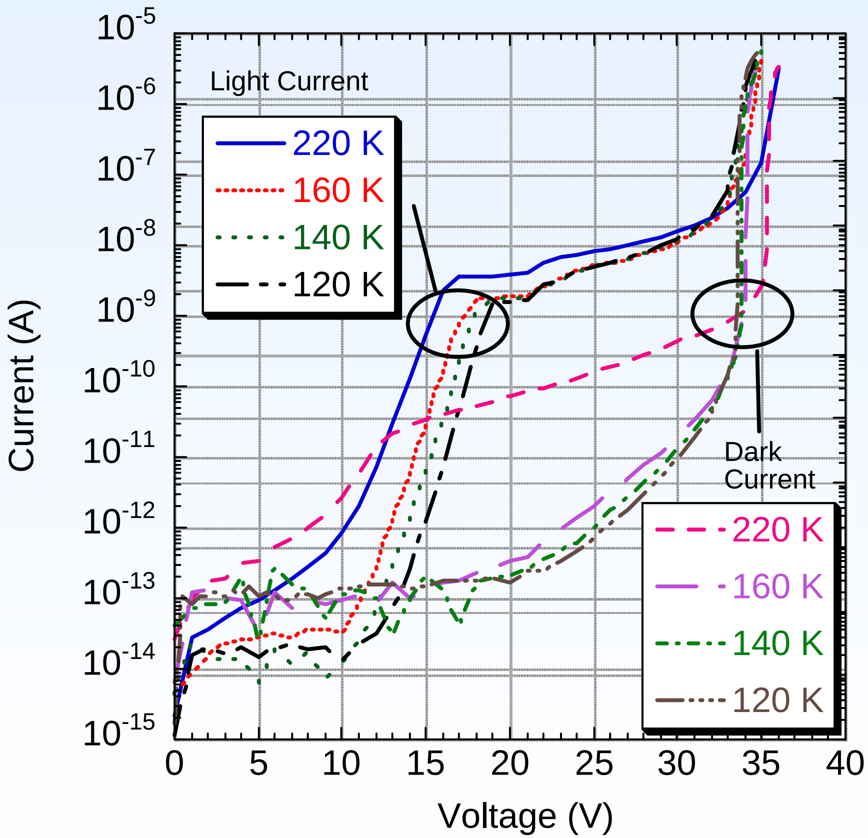


Dark current measurements
Spectrolab custom InGaAs-InAlAs APDs

vs. Area

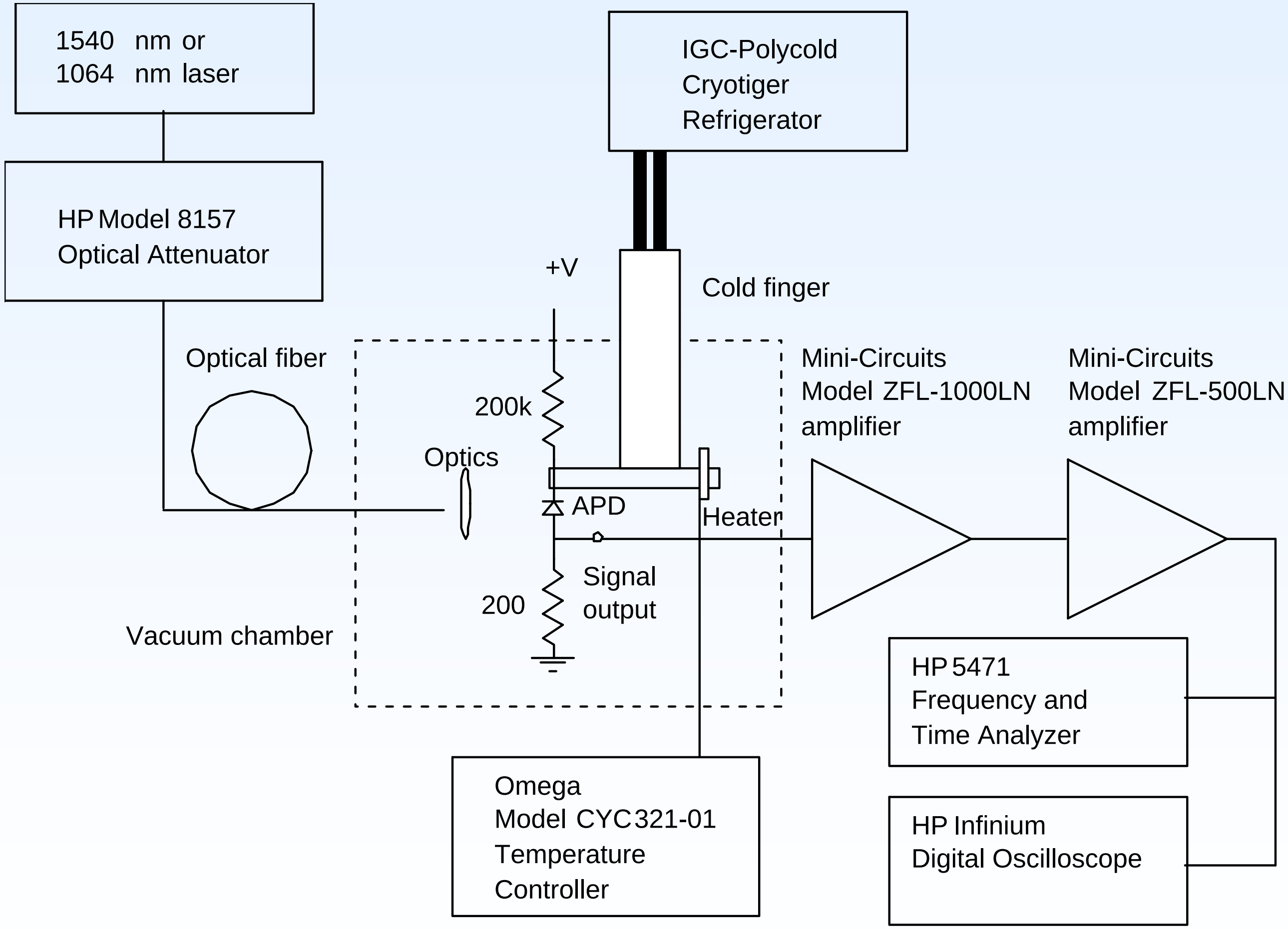


vs. Temperature

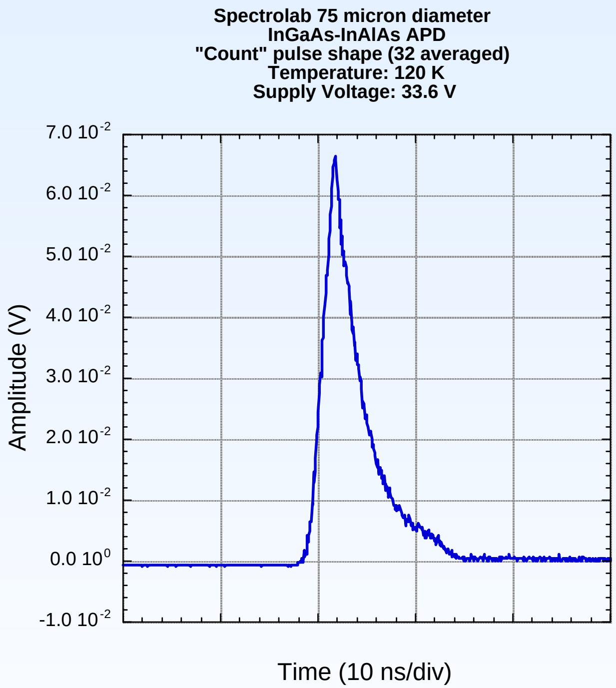


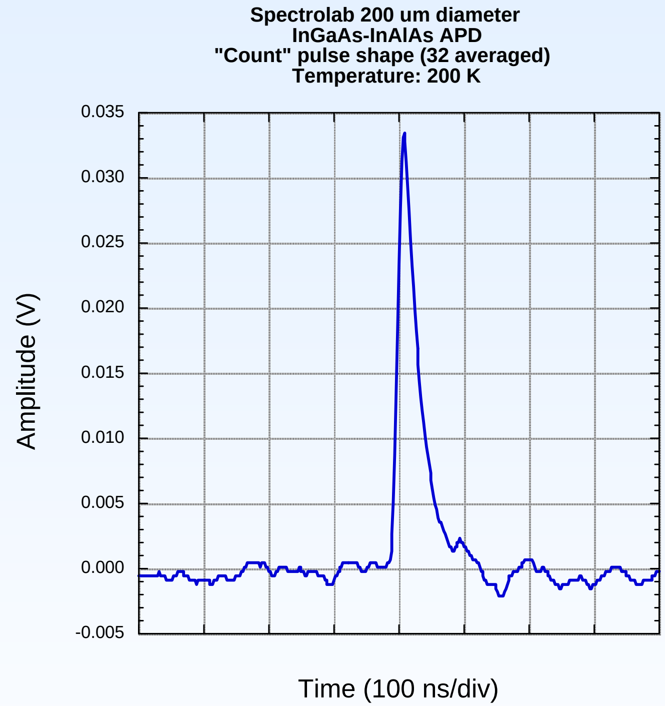
200 μm APD

Photon Counting Experiment Layout



Photon counting with InGaAs-InAlAs APD
Typical photon count electrical pulse





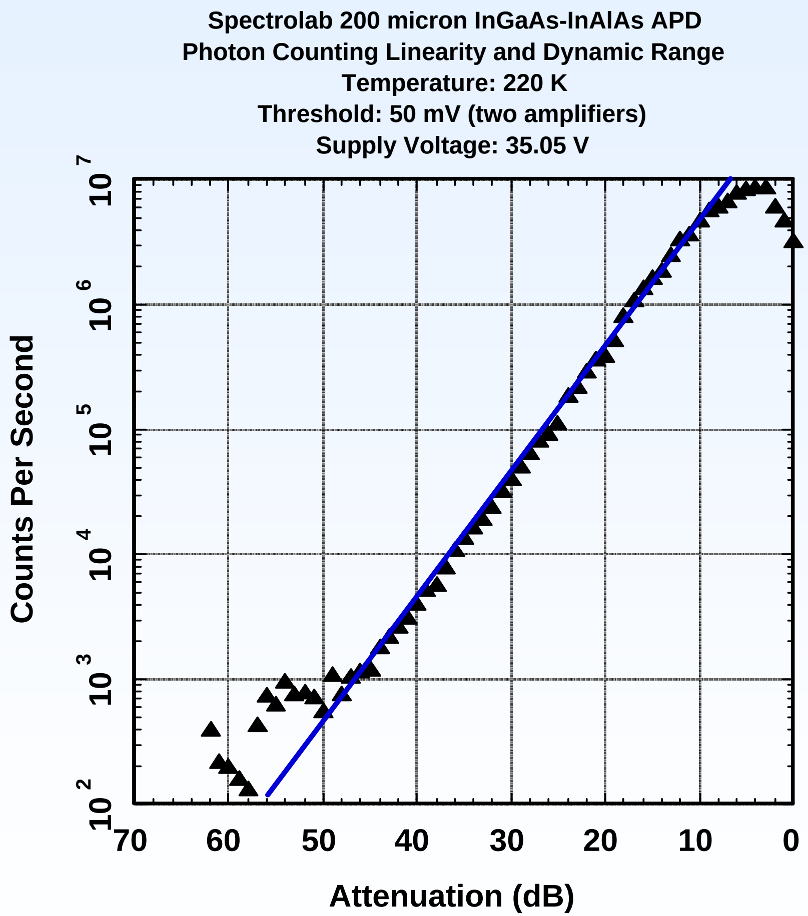
Pulse is bandlimited by:

- the 500 MHz amplifier (rise time)
- the passive quench circuit 200k ohm resistor (fall time)

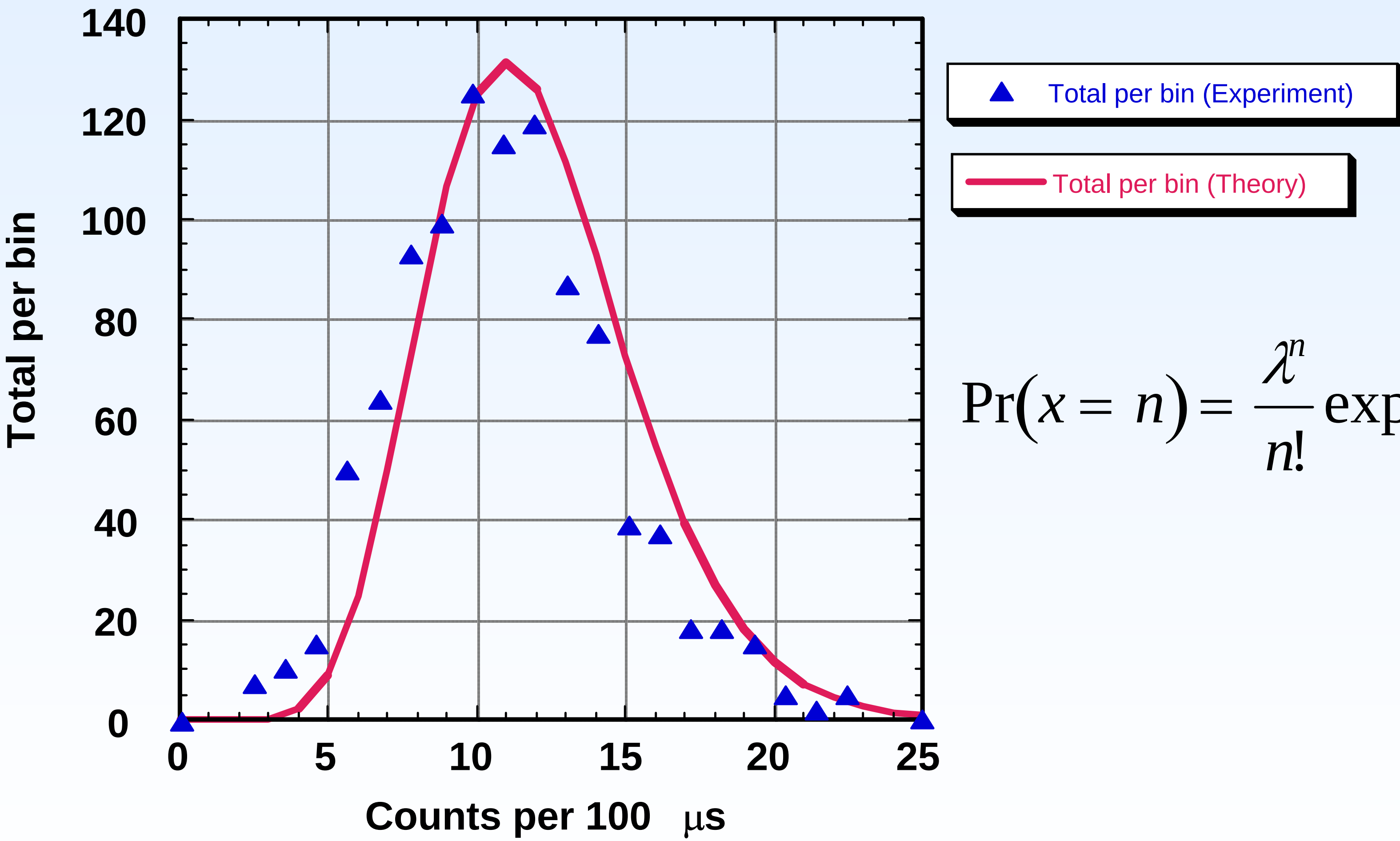
Pulse is bandlimited by:

- the 500 MHz amplifier (rise time)
- the passive quench circuit 2k ohm resistor (fall time)

Photon counting with InGaAs-InAlAs APD
Dynamic Range and Linearity



Photon counting with InGaAs-InAlAs APD
Total count distribution statistics



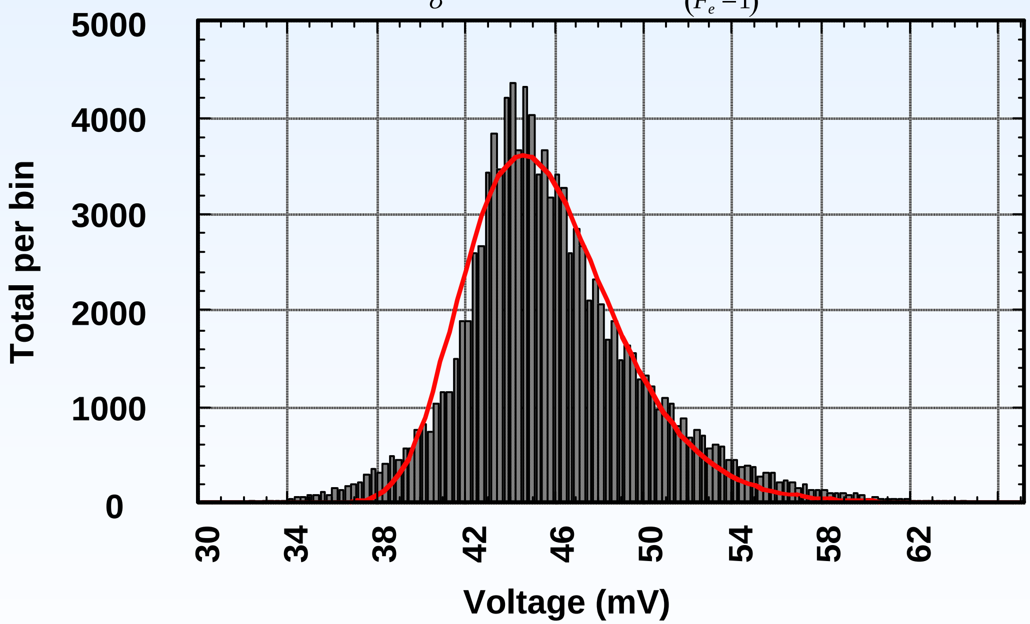
$$\Pr(x = n) = \frac{\lambda^n}{n!}\exp(-\lambda)$$

Total count distribution statistics compared to Poisson theory

Photon counting with InGaAs-InAlAs APD
Pulse height amplitude statistics

$$P(x)=\frac{1}{\sqrt{2\pi}}\frac{1}{\left[1+(x/\lambda)\right]^{3/2}}\exp\left[-\frac{x^2}{2\left[1+(x/\lambda)\right]}\right]$$

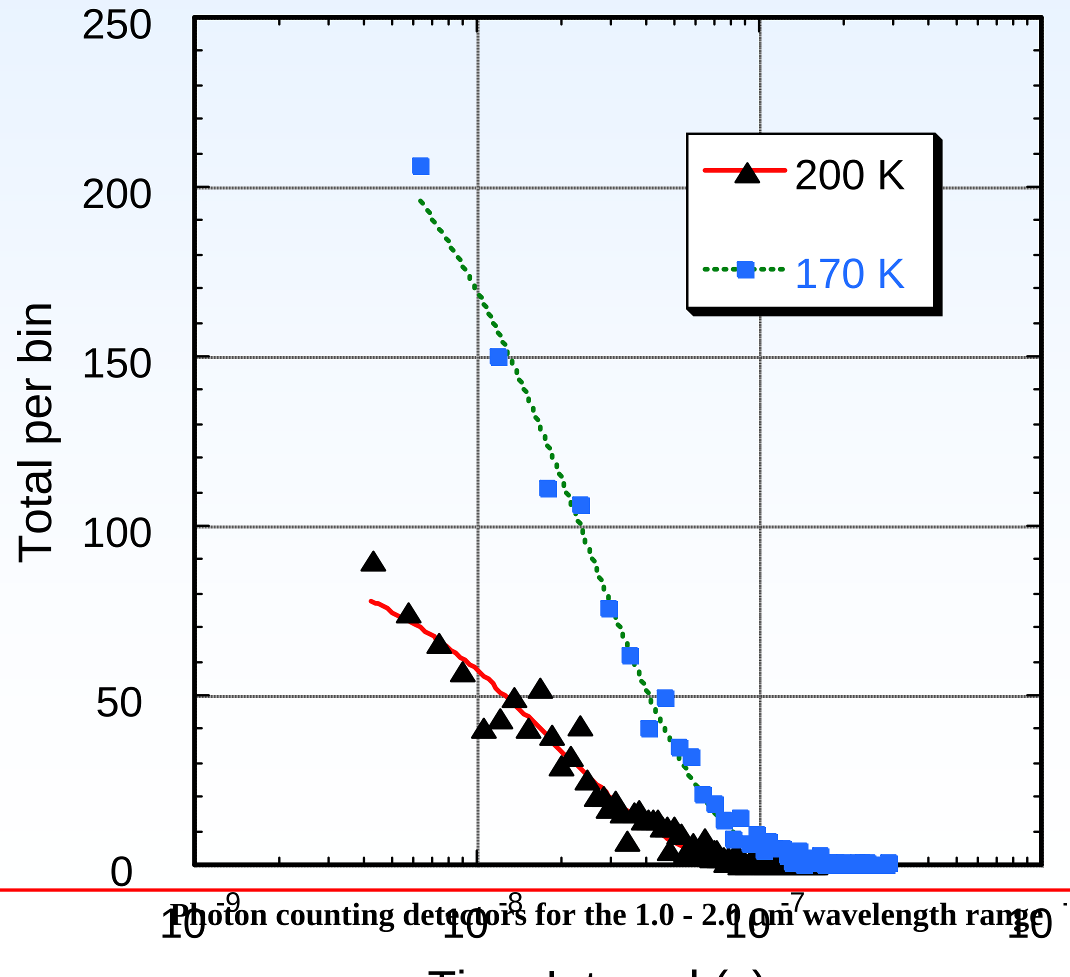
$$x=\frac{m-n_eM}{\sigma},\sigma^2=n_eM^2F_e,\lambda=\frac{(n_eF_e)^{1/2}}{(F_e-1)}$$



Pulse height amplitude distribution
Spectrolab 75 micron APD
Temperature: 120 K
Supply voltage: 33.9 V
Two amplifiers
Scope trigger voltage: 38 mV

Photon counting with InGaAs-InAlAs APD
Interarrival Time Statistics

$$\Pr(x=n)=\frac{(\lambda t)^n}{n!}\exp(-\lambda t)$$



InGaAs-InAlAs APDs
Photon Counting- Context

Previous work on InGaAs-InAlAs

IEEE JOURNAL OF QUANTUM ELECTRONICS, VOL. 39, NO. 10, OCTOBER 2003 1281

Geiger Mode Operation of an $In_{0.53}Ga_{0.47}As$–$In_{0.52}Al_{0.48}As$ Avalanche Photodiode

Gauri Karve, Xiaoguang Zheng, Xiaofeng Zhang, Xiaowei Li, *Student Member, IEEE*, Ning Li, Shuling Wang, Feng Ma, Archie Holmes, Jr., *Member, IEEE*, Joe C. Campbell, *Fellow, IEEE*, G. S. Kinsey, J. C. Boisvert, *Member, IEEE*, T. D. Isshiki, R. Sudharsanan, *Member, IEEE*, Donald S. Bethune, and William P. Risk

Summary of above:

- Preliminary work.
- Used "pseudo" active quench:
- Gated mode:

  - 10 kHz rep rate
  - 2 ns gate "window"

- Achieved 16% Detection Efficiency @ 1550 nm wavelength

Present work here at NASA-GSFC

SPIE LASER RADAR TECHNOLOGY AND APPLICATIONS IX, April 14-15, 2004 Orlando, FL

"Large Area InAlAs/InGaAs Single Photon Counting Avalanche Photodiodes" Joseph Boisvert, Geoffrey Kinsey, Denton McAlister, Takahiro Isshiki, and Rengarajan Sudharsanan, Michael A. Krainak

Summary of present GSFC work:

- Preliminary work.
- Passive quench
- Continuous (non-Gated) mode
- Achieved large dynamic range

Next step: full active quench circuit to simultaneously give continuous mode (w/dead time) and high detection efficiency

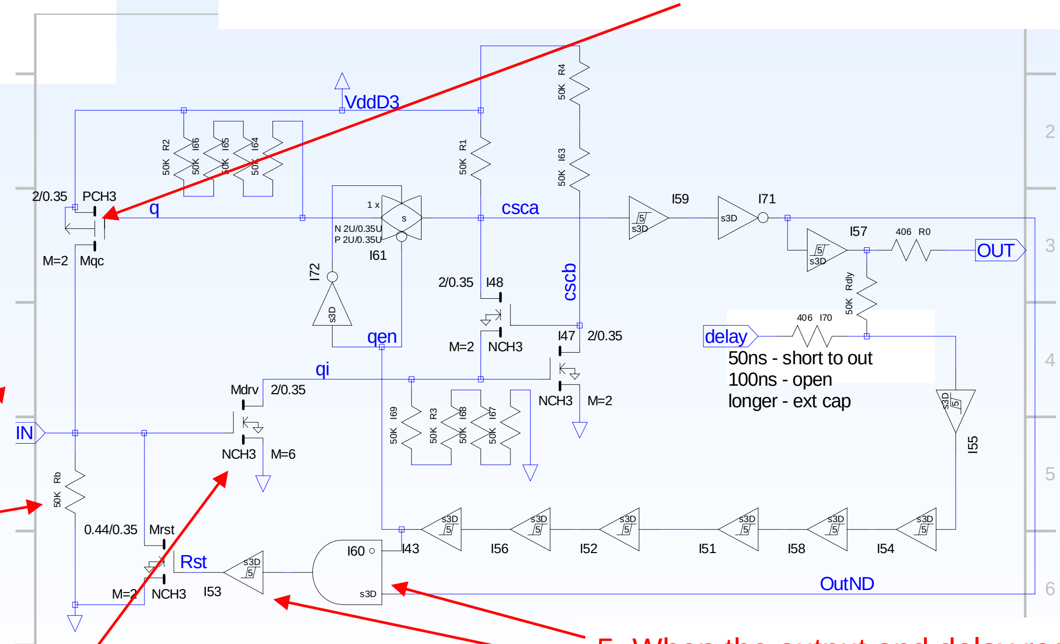
Photon counting with InGaAs-InAlAs APD Status

Detector Parameter	**LRRP Goal**	**Present (4-06-04) Status**
Wavelength range	1.0 - 2.0 microns	Not yet measured (1.0 - 1.7 microns from other references)
Detection efficiency	10 -70%	Passive quench (< 0.1%) Pseudo- active: 16% Active: Pending
Detector size	>200 micron	Photon counting achieved with 75, 200 and 300 micron devices
Dark counts	<100 kcps	< 100 kcps (needs to consider quantum efficiency & device size)
Maximum Count Rate	> 10 Mcps	> 10 Mcps

Active Quenching Circuit

1. APD connects here and the + bias across the APD can trigger an avalanche

4. Mqc will turn on and put +3.3 volts at IN stopping the avalanche

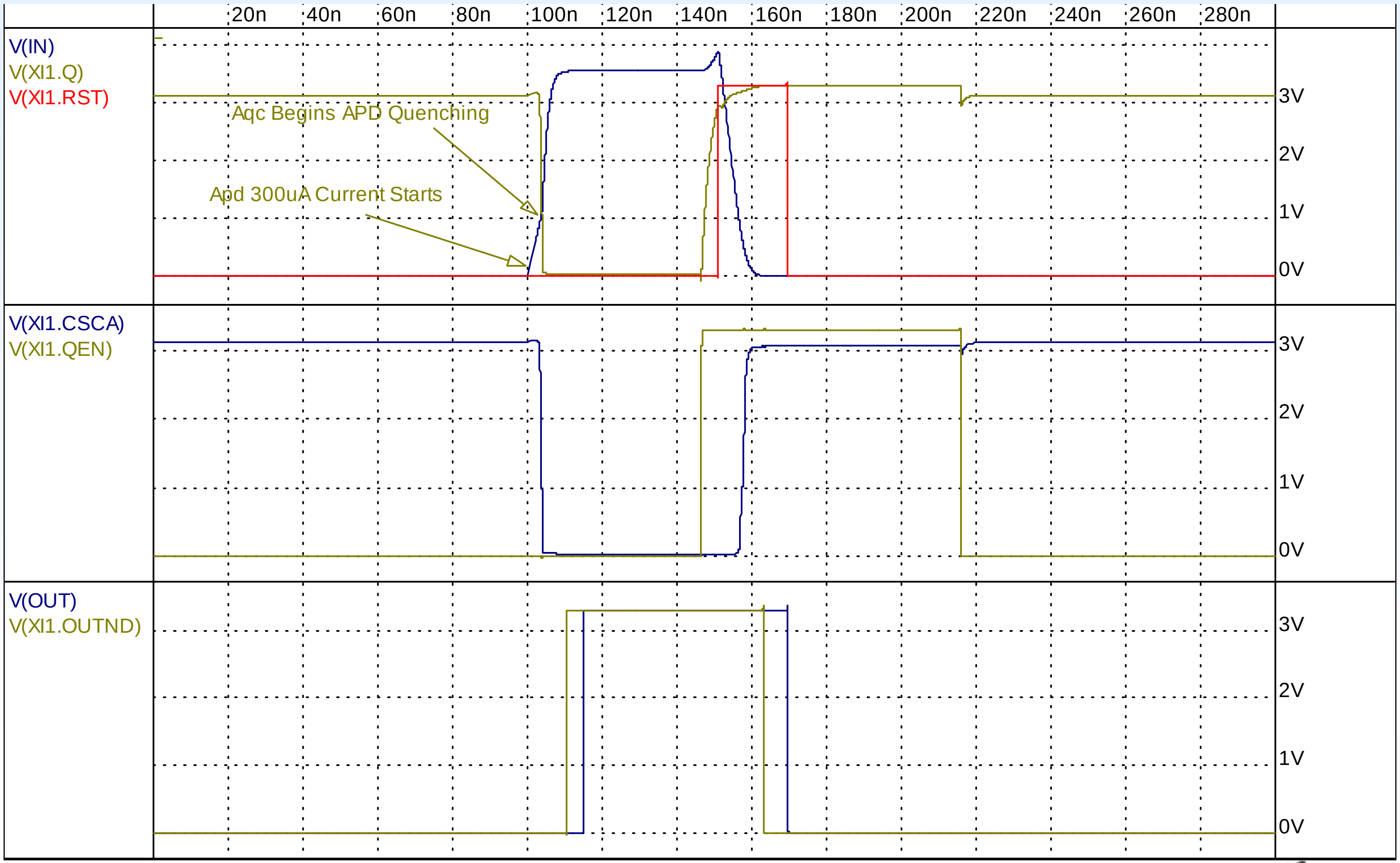


2. When triggered, current flows to ground and the IR drop across this resister turns on this Tx

3. This Tx quenches the APD by turning on Mqc (a complex feedback loop)

5. When the output and delay reach this gate Mqc is turned off and this Tx resets the APD to the trigger level

Active Quench circuit performance
with 300 microamp trigger current (~8 nsec to quench)



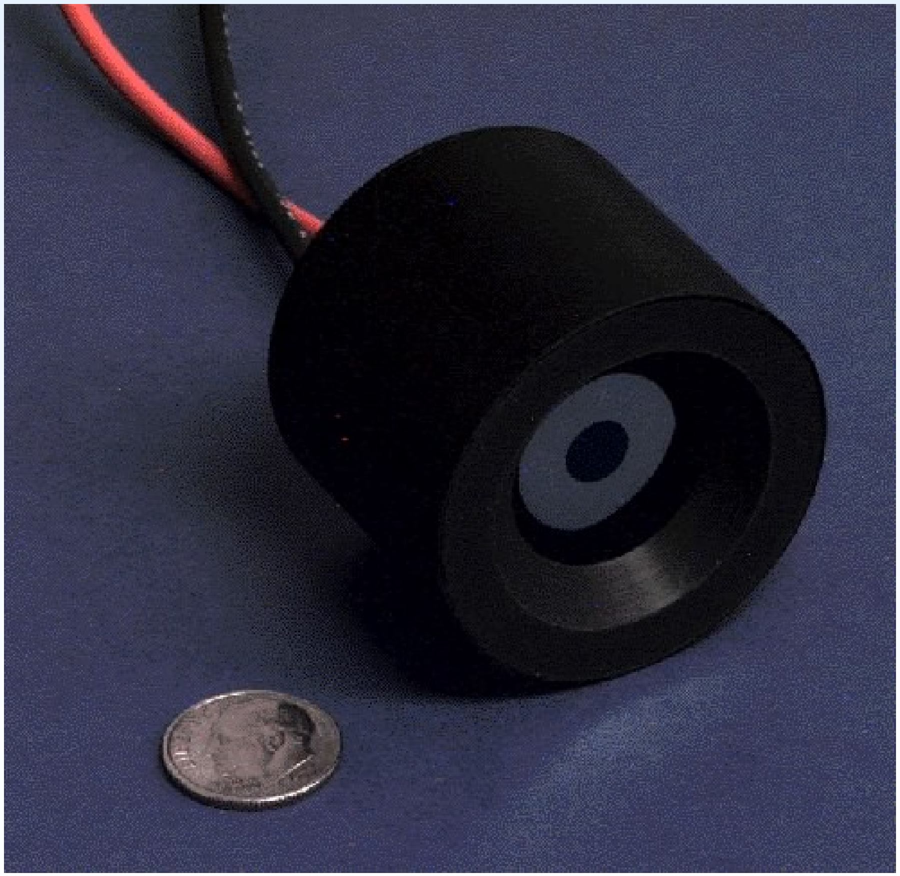
Active quench circuit Performance Summary

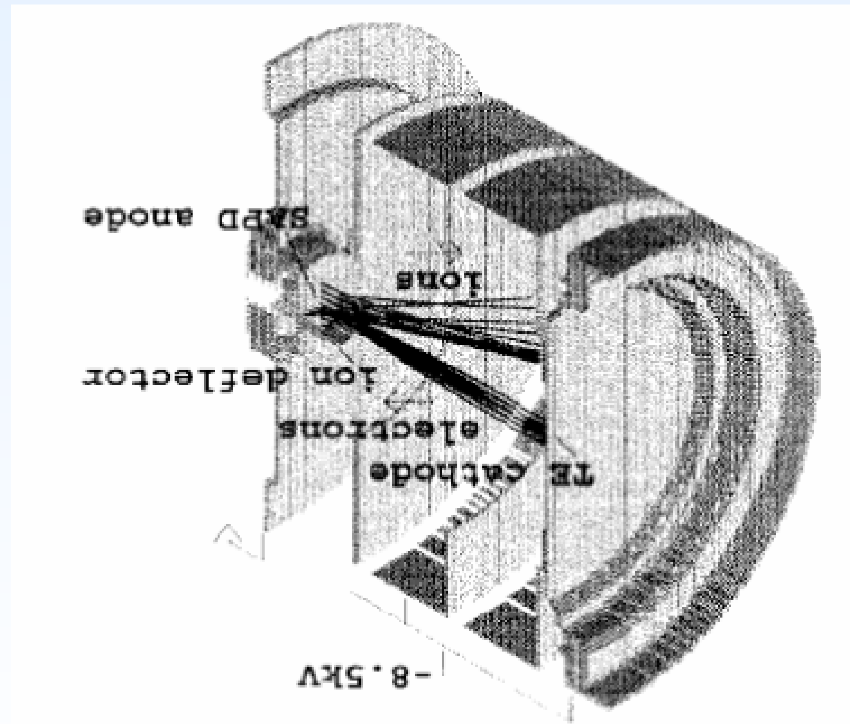
- The active quenching circuit is available for use with a Geiger mode photon counting detector (Voxtel Inc.)
- This circuit quenches rapidly (less than 8 nsec). The quenching will be even faster with a higher trigger current (300 microamps is a low end estimate).
- A change in hold off time is easily accommodated.
- The output from a trigger event is 3.3 volts
- The circuit is being included on an unrelated test chip that had unused area available.

Intevac - hybrid PMT

(a.k.a. intensified photodiode - electron bombarded avalanche diode)

Description





Intevac - hybrid PMT
Wavelength Response

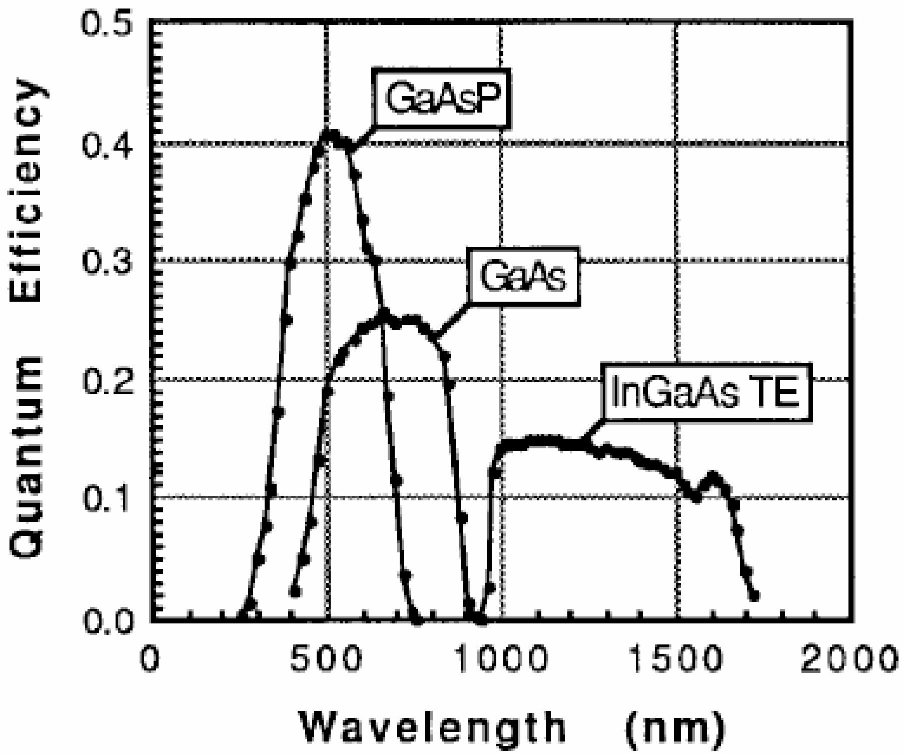


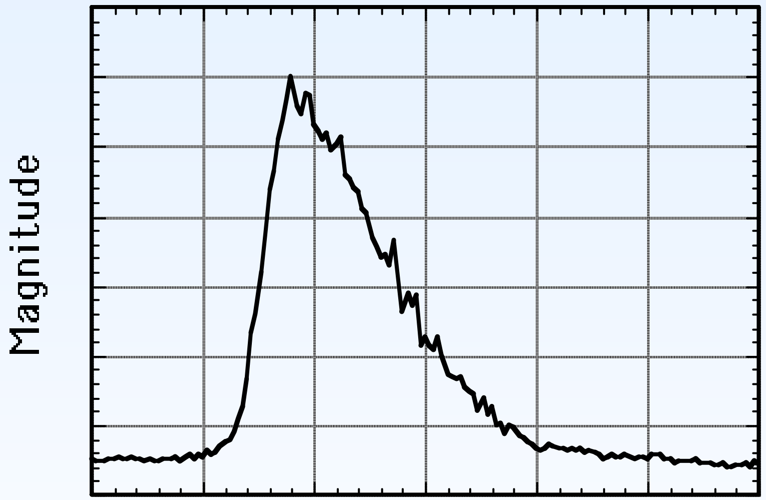
Fig. 1. Measured quantum efficiencies of three III–V photocathodes. The InGaAs TE (transferred electron) photocathode is unique for its high quantum efficiency over the spectral range shown. IPD's have been fabricated with all three photocathodes.

Data at left is from 1997.

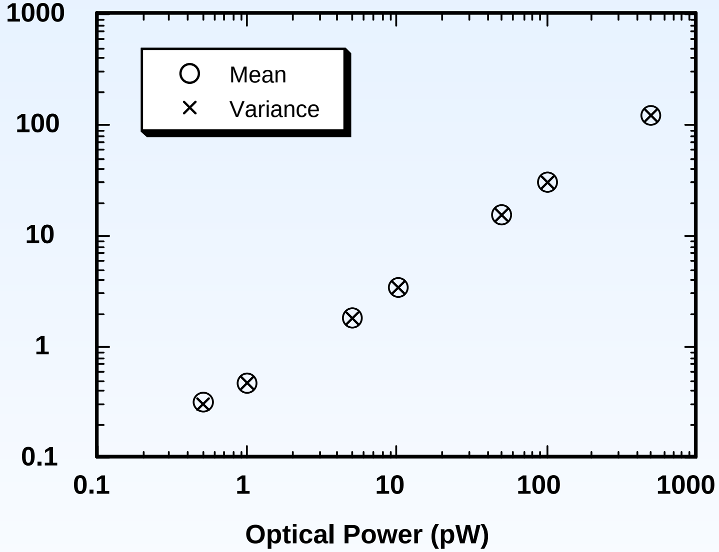
Recently they have achieved:

17% QE at 1064 nm
30% QE at 1550 nm

Intevac - GaAs (820 nm) hybrid PMT (data from 1996) Bandwidth (response time), dynamic range and linearity



Hybrid PMT average photon count waveform.
Rise time = 210 ps, Fall time = 820 ps, Pulse Width = 610 ps

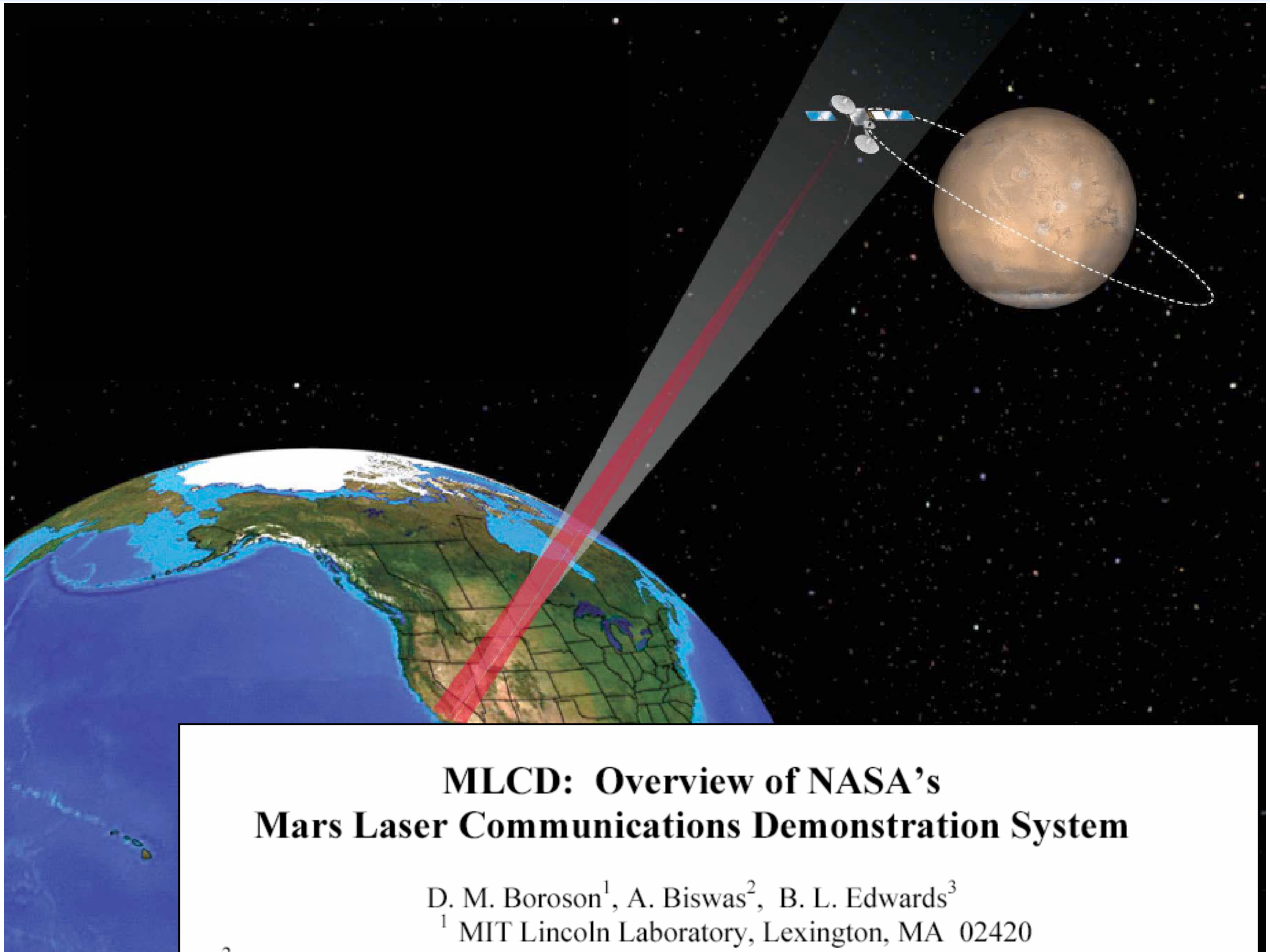


Hybrid PMT
Dynamic Range and Linearity

Mars Laser Communication Demonstration (MLCD)

$270M NASA Project   Launch: 2009

Will use Yb fiber amplifier and photon counting detector (1064 nm)

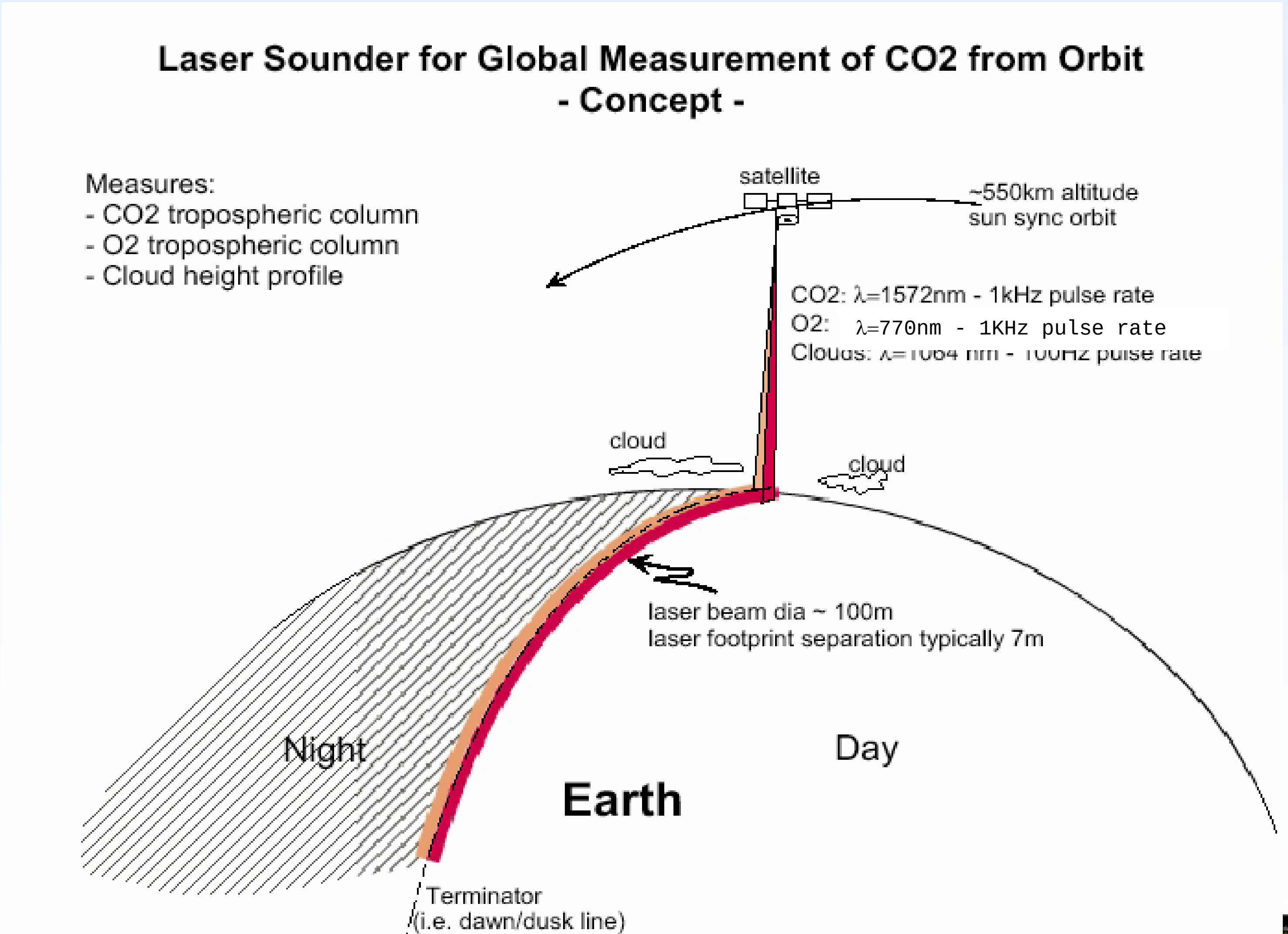


MLCD: Overview of NASA's
Mars Laser Communications Demonstration System

D. M. Boroson[1], A. Biswas[2], B. L. Edwards[3]
[1] MIT Lincoln Laboratory, Lexington, MA 02420
[2] Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109
[3] NASA Goddard Space Flight Center, Greenbelt, MD 20771

Reference: SPIE Photonics West 2004

Laser Sounder for Remotely Measuring Atmospheric CO_2 Concentrations



Photon counting detectors for the 1.0 - 2.0 μ wavelength range

Summary

1. Demonstrated Photon Counting with Large Area (200 μm diameter) InGaAs-InAlAs APDs
   - 40 dB of Dynamic Range!
   - APDs Follow McIntrye Theory:
     - Excess noise
     - Pulse height amplitude statistic
   - Photon Counting Statistics Well Understood

2. Two Conference papers published on recent results.

3. Photon Counting Detector Test Station:
   - NO LIQUID NITROGEN and practical method for 24/7 operation
   - Automated measurement of detector parameters
   - Automated measurement of detector statistics

<u>Future:</u>

- Voxtel Inc. are integrating the Spectrolab Inc. InGaAs-InAlAs APDs with their active quenching circuit (developed under Phase II SBIR), packaging the result by August.
- The active quench circuit should give greatly improved performance over the passive quench circuit.
- Test hybrid PMT.